Supershells and the closest GRB remnants

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ABSTRACT

Following recent suggestions of a gamma-ray burst origin of large ISM holes (supershells) detected in the galaxy, we discuss the effects of the recently discovered shell GSH 238+00+09 (and other nearby extremely energetic supershells) on the earth's atmosphere. We argue that the large flux of gammas from these specific events would have provoked major catastrophes to living organisms. The lack of evidence for the latter can then be used to rule out local isotropic nearby GRBs in the last tens of Myr and another origin for large supershells is likely. Alternatively, this argument may be taken as independent evidence for beaming of the gamma rays, although statistics are not yet sufficient to constrain the beaming angle better than $\sim$ tens of degrees. The effects of less-energetic events of the type of SN1998bw are also considered. It is shown that more than a dozen of them should have occurred within $40(E/10^{48} erg)^{1/2}\, pc$ of the earth in the last 500 Myr with similar effects. Beaming of the latter would also alleviate the conflict, although another likely possibility (an actual rate much smaller than $10^{-4} yr^{-1}$) may be a solution, at the same time avoiding an excessive number of supershells active in the galaxy.

Subject headings: Gamma-ray bursts - Galactic supershells - ISM

1. Introduction

A breakthrough in GRB astrophysics has been achieved by the observation of afterglows located ∼ few hours after the event with unprecedented positional accuracy (Costa et al. 1997). The presence of absorption lines (Metzger et al.1997, Kulkarni et al.1998a) in some of these afterglows has convinced most researchers that most (if not all) of the GRBs are extragalactic, although a through comprehension of the bursts is still far away since the sources have yet to be identified and the physics of the afterglows addressed (see, for example, Rees 1997, Hurley 1998). Nevertheless, we may now assert that a distance scale (and hence an energy scale) is available for "classical" bursts. Regardless of the specific source, it is now clear that the evidence points out to E_γ as high as $\simeq 10^{53}\, erg$ for the most energetic bursts (Kulkarni et al.1998b) if the gamma emission is isotropic.

While the study of distant, frequent bursts continues, the observations have undoubtedly risen a number of questions related to the occurrence of GRBs in the *local* universe. Thorsett (1995) has discussed the effects of a close GRB on the earth's biosphere (see also Dar, Laor and Shaviv 1998 for a related discussion). The issue is timely since it has been shown that a burst must occur as often as $(0.3 - 40)\ Myr$ per L_*, depending on the evolution of the sources (Wijers et al.1998). Loeb and Perna (1998) have further suggested that most of the HI supershells could be the remnants of GRBs. In fact the latest data on GRB afterglows strongly suggest that some remnants must be found in a given normal galaxy, since they should not dissipate before ∼ tens of Myr. The two gigantic shells found by Rand and van der Hulst 1993 in NGC 4631 are perhaps the most clear examples that ∼ kpc-sized shells requiring $\sim 10^{54}\, erg$ of input energy are real since their identification is neater in external galaxies.

As discussed elsewhere (Chevalier 1974, Heiles 1979, Tenorio-Tagle and Bodenheimer 1988) the initial total energy of the expanding shell E_E is inferred from the theory of explosions in a uniform medium. In the limit where the internal pressure is no longer important, a numerical fit

(Chevalier 1974) yields

$$E_E = 1.2 \times 10^{53} \left(\frac{n_0}{cm^{-3}}\right)^{1.12} \left(\frac{R}{kpc}\right)^{3.12} \left(\frac{v}{kms^{-1}}\right)^{1.4} erg, \tag{1}$$

where n_0 is the particle number ambient density, R is the radius of the shell and v is the expansion velocity. The timescale at which the supershell velocity is decelerated to $\simeq 8\, km\, s^{-1}$ (the observed r.m.s. velocity of the interstellar clouds) is $\tau = 0.31\, R/v \simeq 37\, (R/1\, kpc)(v/8\, km\, s^{-1})^{-1}$ Myr. Since these estimates are derived from the simplest models (assuming spherical symmetry, uniform density, etc.); there could be considerable uncertainties when E_E and τ are inferred from the observed data (see, e.g. Heiles 1979).

While all the hitherto identified galactic supershells lie several kpc away from the sun ($< D >$ $= 9.6\, kpc$ for the Heiles 1979 compilation of expanding shells), the identification in HI, IR, radio continuum and soft X-rays of a new, nearby supershell has raised again the question of the relationship to GRBs and possible biological effects. GSH 238+00+09 (Heiles 1998) is not only a major galactic supershell, but is also the only closer than $1\, kpc$. If, as argued by Loeb and Perna 1998 (see also Blinikov and Postnov 1998 and Efremov, Elmegreen and Hodge 1998), the supershell is the remnant of a galactic GRB we may be have an unprecedented opportunity to correlate directly cosmic explosions of this kind with fossil records.

2. Gamma ray fluxes onto the earth and the ozone layer

We have searched other large-energy shells in the catalogue of Heiles 1979 and found several candidates (listed in Table 1) that, if identified with remnants of GRBs, should have affected the earth in a very dramatic way (see below). It should be stressed that, mainly due to the difficulty of identifying true large structures inside the galaxy, this selection is far from definitive. For the sake of the argument and definiteness we shall address the objects in Table 1 only.

Consider the case of the simplest, ”standard candle” scenario for GRBs. Given the geometrical centroids of the supershells we may estimate immediately the flux of gamma-rays at the typical passband 30-2000 keV at the top of the atmosphere ϕ. Table1 (column 6) displays these estimates

for an assumed energy in gamma-rays of $E_\gamma = 10^{53}\,erg$. Since the true luminosity distribution function is still an unsettled question and there might be a considerable spread between the events, other possibilities should be considered. Since this is a somewhat extreme assumption (although the continuing evidence for $\sim 10^{53}\,erg$ from GRB 971214 lends some support to it, see Odewan et al.1998), we expect these numbers to be upper limits.

Thorsett (1995) pointed out that GRBs this close would (because of the huge gamma fluxes of Table 1) have produced deep effects on the biosphere. The destruction of a substantial amount of the ozone layer along a $\sim 10\,s$ typical burst duration is the most obvious one, and seems inescapable since the $\geq 10^7 erg\,cm^{-2}$ gamma fluxes of Table1 are in fact larger than the equivalent total chemical energy of the fragile ozone layer.

EDITOR: PLACE TABLE 1 HERE.

As discussed by Schramm and Ellis 1995 (see Ruderman 1974 for the first through discussion of a closely related event), several general features of the incidence of a huge gamma flux can be worked out with confidence. For example, it is well established that the production of large concentrations of odd nitrogen NO_x is very harmful for the fragile ozone layer shielding the earth from solar UV radiation. The dominating catalytic reactions are

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{2}$$

$$NO_2 + O \rightarrow NO + O_3 \;, \tag{3}$$

since their efficiency of ozone destruction is high. The additional NO produced by the ionizing gamma flux will greatly enhance the penetration of solar UV because the former is expected to be much higher than the steady production by normal cosmic rays. The rate of production of NO (in mol/cm^2) is

$$\xi = 10^{17}\phi_7 \left[\frac{13}{10+y}\right] \;, \tag{4}$$

where $\phi_7 \equiv (\phi/10^7 erg\,cm^{-2})$ is the incident gamma flux scaled to a reference value, and the factor in brackets is the ratio of efficiencies of the steady production to the GRB flash in the stratosphere.

Dividing ξ by the stratospheric column density and converting to parts per billion, we derive the abundance of NO produced by the GRB flash as the physical solution of a quadratic equation, very well approximated by

$$y_{flash} \simeq 51\phi_7^{1/2} - 5. \tag{5}$$

Thus, the ratio of produced $[NO]$ to the present ambient $[NO]_0$ is given by $X = (3 + y_{flash})/3 \sim 16\phi_7^{1/2}$. Such a great abundance of NO would remain in the stratosphere for a mean residence time of $< \tau >= 4\,yr$, which is much larger than the homogenization time of the atmosphere. Thus, once produced by the flash the ozone layer would be affected for a period at least as large as the mean residence time of the catalyzer.

The approximate formula employed by Ruderman 1974 and Schramm and Ellis 1995 to estimate that reduction is

$$\frac{[O_3]}{[O_3]_0} = \frac{(16 + 9X^2)^{1/2} - 3X}{2}\,, \tag{6}$$

expected to be accurate to within a numerical factor. To be conservative we shall regard as "catastrophic" those GRB producing a flux ϕ which kills at least 90% of the present O_3 layer through NO enhancement (actually it is highly likely that $\sim$ tens percent O_3 destruction would trigger massive biological death). Imposing that figure we obtain a lower bound on ϕ

$$\phi \geq 0.7 \times 10^7\,ergcm^{-2}\,, \tag{7}$$

above which it is difficult to envision survival of the species. This bound can be seen in Fig.1 , depicting at once the fraction of surviving O_3 as a function of the incident flux ϕ_7 . In other words , it is safe to state that all supershells listed in Table 1 would have trigger a massive extinction of life through the ozone destruction . Thus , either the association is incorrect or beaming is necessarily involved in the emission.

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Fig. 1.— The survival fraction of ozone ($[O_3]/[O_3]_0$ after the incidence of a gamma flux ϕ (in

$10^7\,erg\,cm^{-2}$ units). The hatched region corresponds to a destruction fraction which would have caused a major extinction pattern. Compare with the values in the last column of Table 1

In order to justify the assumed effects onto the biota we shall estimate, using a simple model, the killing timescale of a marine unicellular organism population exposed to the UVB (260-320 nm) radiation imediately after the burst. For the bursts of Table 1 it is a good approximation to put that the afterburst solar UVB flux at sea level will be comparable to the one measured today at the top of the atmosphere $F_\lambda = 0.2\,W\,cm^{-2}\,\mu m^{-1}$. The simplest theory of cell mortality by absorption of UV photons predicts the number of microorganisms to evolve according to

$$\frac{N}{N_0} = 1 - (1 - \exp(-\kappa D))^m \tag{8}$$

where D is the dose (here defined as $\int F_\lambda\, d\lambda$) and m is the number of photons necessary to kill the cell. We shall apply this model to a marine population assumed to be distributed exponentially with a depth scale z_0 (without day-night circulation) having a spontaneous reproduction rate η. If N_s is the number of organisms at $z = z_0$ and the coefficient of attenuation for UVB photons in marine water is z_1 we find that the temporal evolution of this population at any depth will be given by

$$N(z,t) = N_s \exp(-z/z_0)\, \exp[(\eta - \xi(z))t] \tag{9}$$

with $\xi(z) \simeq \kappa F_{\lambda 0}\, \Delta\lambda \exp(-z/z_1)$. Now we may ask which is the time for killing 90% of these organisms once the UVB flux incides onto the sea surface, denoted as τ_{90}. If we normalize the mortality curve using the data from modern bacteria (i.e. *Escherichia Coli*) we obtain for this time $\tau_{90} = 0.4 \exp(z/z_1)\, s$. Therefore, it is concluded that simple marine organisms, and especially those capable of photosynthesis, will be killed almost instantaneously unless they "hide" at several tens of z_1, in practice $\geq 100m$ for a time as long as the healing of the ozone layer. Terrestrial organism behavior are much more difficult to model, although it has been long sice the '50 that mammals would not survive longer than $\sim 1s$ without ozone. Even though simple models may be

oversimplified, we believe that the essential points of a mass extinctions are adequately illustrated beyond any reasonable doubt.

The gamma shower would have produced other unique catastrophes as well. The production of $\sim\ 10^9\,tons$ of NO_x enhancing the acid rains and the screening effects of NO_2 to the sunlight (with possible dramatic cooling effects, see Reid, McAfee and Crutzen 1978) are just two of them. To address these issues properly, the actual possibility of a close GRB calls for a through study of the dynamical response of the biosphere to a large perturbation, since all the effects are deeply interwoven and it is quite difficult to isolate them due to their non-linear character.

3. SN1998bw and supershells

The reports (Galama et al. 1998, Kulkarni et al.1998a) on the remarkable type Ic supernova SN1998bw have prompted an intense discussion in the literature on the nature of (some) core-collapse events (see Woosley, Eastman and Schmidt 1998, Wang and Wheeler 1998). The most unusual characteristics of this event are perhaps the early, strong radio emission (Kulkarni et al.1998a), and the likely association (Galama et al. 1998) with GRB 980425. Striking as these features are, we here suggest that SN1998bw energetics may also hold a clue for another long-standing puzzle of ISM structure and evolution, namely the occurrence of supershells for which a growing body of observations (Heiles 1998, Heiles 1984 and references therein) is available.

Two separate groups (Iwamoto et al.1998, Woosley, Eastman and Schmidt 1998) attempting to model the light curve and observed spectra have shown that the event can be understood as the spherically symmetric explosion of a massive star with the ejection of $\geq\ 10\,M_\odot$ of material including $\sim\ 0.5\,M_\odot$ of ^{56}Ni. This gives in turn kinetic energies of $\sim\ 3\times10^{52}$ erg (once the slightly different adopted distances to the galaxy ESO 184-G82 are matched). Alternatively, an asymmetric explosion has been advocated by Höflich, Wheeler and Wang 1999 which would in turn bring the ^{56}Ni mass down to $0.2\,M_\odot$ and the energy of the explosion to $\sim\ 2\times10^{51}$ erg. While asymmetric models share the attractive feature of being more akin to standard core-collapse

supernovae from the energetic and nucleosynthetic grounds, the radio data gathered by Kulkarni et al.1998b do not seem to show the expected high polarization of a jet-like explosion. In fact, as already mentioned by these authors, the low polarization is indeed consistent with the simplest spherical blast wave models. While spherical models are in serious trouble for producing a GRB, their energetics are much better tested than the GRB production mechanisms, and are derived independently of the latter. Therefore, it seems that the existence of large, single stellar explosions should be considered seriously (see Iwamoto et al.2000 for additional evidence of a second possible hypernova).

If we repeat the calculations of the previous section and demand the same level of ozone destruction to trigger a biological catastrophe, we may derive instead an upper bound to the distance at which a "SN1998bw" would be harmful. This distance is

$$D \, < \, 40 E_{48}^{1/2} \, pc \, , \tag{10}$$

and we have scaled the energy in gamma rays to $E_{48} = (E/10^{48} erg)$. A consideration of the quotient of the galactic disc to the volume defined by the distance eq.(8) gives us an idea of the frequency of the events inside the latter if the galactic rate is known. Adopting a "SN1998bw" rate of $\sim \, 10^{-4} yr^{-1}$, we obtain an effective rate for events closer than D of $\simeq \, 3 \times 10^{-8} yr^{-1}$. Thus we expect $\sim$ 15 events in the last 500 Myr harmful for the ozone layer unless modest beaming is present. However, even for isotropically emitted gammas, a much lower galactic rate would not only solve this problem but also reduce the number of active remnants to tolerable levels, as pointed out above. To be sure, it is quite difficult to discriminate between "classical GRB"-generated and "SN1998bw"-generated supershells (indeed, some of the objects in Table 1 could belong to the latter instead of the former); but the conflict of the number of remnants will arise with a high rate of $\sim 10^{-4} yr^{-1}$ simply because they live much longer in the ISM than their lower energy, garden variety supernova cousins.

Precise determinations of the rate ξ of explosion of such energetic supernovae are not yet available, although it is expected that a few of them should be present if $\xi \, > \, \tau^{-1}$, where τ is the lifetime of the supershell. Inserting the expression for τ given in section 2 we conclude that a

handful of "active" energetic supernova-generated shells if their rate is higher than $\sim 3 \times 10^{-8}$ yr^{-1}, which is almost two orders of magnitude lower than the model-independent estimate (Paczyński 1993) for classical GRBs and consistent with SN1998bw-type events being ten millon times more rare than normal core-collapse supernovae (see Wang and Wheeler 1998). [3] Thus we think that there is ample room for an actual galactic rate much lower than $10^{-4} yr^{-1}$ from this argument. By definition, supershells carry an energy of at least tens of normal supernovae. The possible importance of the SN1998bw event resides precisely in that its large inferred energy comes to fill the gap between these two extremes, in spite of widely different inferred gamma energies. It is indeed worthwhile to note that the energy attributed to this supernova is within $\sim$ 10% of the value required to produce the latest identified (Heiles 1998) supershell GSH 238+00+09 with a centroid at only $\sim$ 0.8 kpc away from the Sun. These estimates suggest that very energetic supernovae, unfrequent as they might be, are possibly an important component for ISM morphology and evolution, with consequences for stellar formation and related topics. Recent claims of detection in X-ray bands Wang and Chu 1999, Wang 1999 need a follow-up to confirm the energetics and to gather a statistically significative sample for the sake of deeper analysis.

4. Conclusions

We have shown that the tentative identification of supershells with GRB remnants leads to a definite conflict with biological records, since the derived gamma fluxes onto the earth are enormous and should then correlate with several massive extinctions of life in the past $\sim 40 Myr$. Of course this does *not* mean that some galactic GRB(s) could not have affected the biology on

[3] A very recent study by Frail et al. 2001 claims a lower energy scale (and a correspondingly higher frequency of the events by a factor $\sim$ 500) that can be analyzed using the results presented above.

earth [4] , since epochs earlier than the lifetime of the shells remain untested because it is impossible to find the (now extinct) remnant supershell. If the supershells are indeed GRB remnants and the gamma emission is beamed, the potential conflict would vanish, although we estimate that the present database of supershells would have to be enlarged by a factor of ~ 3 to constrain the gamma emission to cones opening $\leq$ 20 degrees. It is likely that we will know the actual beaming by other methods much sooner.

The consideration of a lower energy (possibly associated with SN1998bw-like events) suggested also a modest beaming effect (already discussed, for instance, by Höflich, Wheeler and Wang 1999 but from a completely different point of view than ours) and/or the existence of a much lower rate to avoid overproduction of "hypernovae" remnants. A clue to the energetics may be hidden in the discrepancy between the theoretical injection energy E_E (Iwamoto et al.1998, Woosley, Eastman and Schmidt 1998), amusingly sufficient to match exactly the energy derived for GSH 238+00+09, and the energy of its associated GRB 980425 (Soffitta, Feroci and Piro 1998)

We suggest that the preliminary consideration of the rate of these SN-GRB type of events (Wang and Wheeler 1998) and their lifetimes is nevertheless sufficient to consider them as serious candidates for the progenitors of supershells. A closer examination of the latter and modelling of the specific features of the former (as opposed to the multiple-supernova-wind model) could prove useful to reassess the formation and evolution of supershells. Clearly, much work is needed before we pinpoint and understand the nature and consequences of these events for the ISM and biological activity with confidence.

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[4] It is interesting (but perhaps not significative) to note that GSH 139-03-69 should have been almost simultaneous with the Priabonian extinction around 35 Myr ago where cool-temperature-intolerant organisms gradually died, whereas GSH 242-03+37 has a characteristic age of 7.5 Myr where even ^{10}Be marine sediments could be used for testing purposes (Morris 1991).

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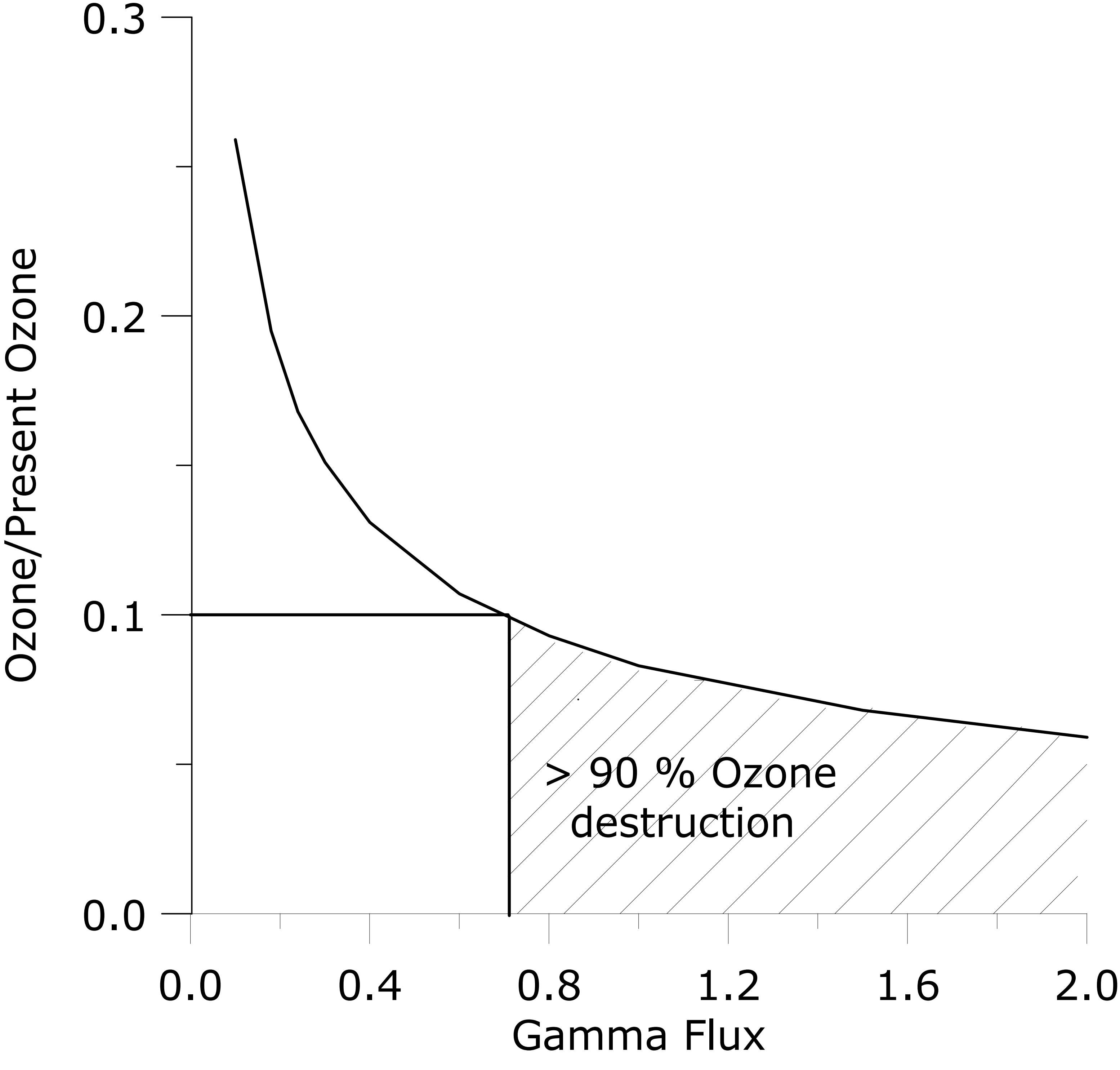
Table 1. Features of selected supershells.See text for details

Shell GHS	D (kpc)	$v\,(km\,s^{-1})$	$\log E_E$	$\tau\,(Myr)$	$\phi(erg\,cm^{-2})$
238+00+09	0.8	9	52.5	21	1.4×10^9
041+01+27	2	10	52.9	7.4	2.2×10^8
075-01+39	2.6	22	52.9	2.7	1.3×10^8
108-04-23	2.5	16	52.7	3	1.4×10^8
242-03+37	3.6	20	54.2	7.4	6.8×10^7
061+00+51	4.8	14	52.1	33.5	3.8×10^7
016-01+71	6.3	18	52.4	20	2.2×10^7
139-03-69	7.1	18	54.8	33	1.7×10^7
224+03+75	7.6	14	53.4	13	1.5×10^7
029+00+133	8.7	20	52.6	6	1.2×10^7



0.3
0.2
0.1
0.0
Ozone/Present Ozone
> 90 % Ozone
destruction
0.0
0.4
0.8
1.2
1.6
2.0
Gamma Flux